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NASA Project Apollo Working Paper No. 1038

# PROJECT APOLLO

# PROPULSION REQUIREMENTS FOR LUNAR LANDING MISSIONS EMPLOYING A DETACHABLE LUNAR LANDER

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

MANNED SPACECRAFT CENTER

Langley Air Force Base, Va.

December 19, 1961

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# PROPULSION REQUIREMENTS FOR LUNAR LANDING MISSIONS EMPLOYING A DETACHABLE LUNAR LANDER


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NASA - Manned Spacecraft Center
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August 15, 1962

## ERRATA

The enclosed pages are revisions to the Project Apollo - Propulsion Requirements for Lunar Landing Missions Employing a Detachable Lunar Lander. These pages replace correspondingly numbered pages in the NASA Project Apollo Working Paper No. 1038 dated December 19, 1961. It is suggested that the replaced pages be destroyed as directed by security regulations.

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# EMPLOYING A DETACHABLE LUNAR LANDER

## SUMMARY

For lunar landing missions employing a lunar lander detachable from the main craft in lunar orbit, the expressions for the earth-return payload and lander weights are developed for staged and unstaged shuttle and main craft propulsion systems. Relative effects of variables such as propellant boiloff, velocity requirements, specific impulse, and mass fractions, as well as staging and shuttle and earth-return weights are evaluated. It is shown that no real advantages exist in staging either the shuttle or the main craft.

## INTRODUCTION

Consideration has been given recently to the use of a detachable manned vehicle for lunar landing which would separate from the main craft in lunar orbit, land and return to the main craft. This vehicle, referred to as the lunar lander or shuttle, would be capable of supporting one or two men for a limited time and would be jettisoned after recontact with the main craft in lunar orbit.

There is a limiting gross weight of the lander system that will be compatible with the Apollo mission propulsion system when the latter is used for lunar-orbit injection and ejection in support of the lunar-lander concept.

Another major effect to be considered is the launch-vehicle capability since the earth-escape weight for the lunar-lander mission exceeds the earth-escape weight for the nominal Apollo lunar orbit mission.

In order to fully evaluate the impact on the Apollo launch and spacecraft technique, it becomes necessary to develop the expression for the earth-escape weight in terms of the various parameters effective. Each parameter is to be investigated in order to evaluate its relative influence on the system design.

The nominal velocity increment requirements for the mission listed in appendix A were obtained from the NASA Manned Spacecraft Center Astromechanic and Navigation Section. These velocity requirements are nominal and do not include reserves for either guidance errors or propulsion deficiencies.

## SYMBOLS

| | |
|---|---|
| a | ratio of propellant boiloff per day to initial propellant weight of the lunar orbit insertion system, $\frac{\text{W boiloff per day}}{\text{W total propellant}}$ |
| b | ratio of propellant boiloff per day to initial propellant weight of the lunar ejection system, $\frac{\text{W boiloff per day}}{\text{W total propellant}}$ |
| $f_1$ | mass fraction of the midcourse system(s), $\frac{\text{W propellant}}{\text{W total}}$ |
| $f_2$ | mass fraction of the lunar insertion system, $\frac{\text{W propellant}}{\text{W total}}$ |
| $f_3$ | mass fraction of the lunar ejection system, $\frac{\text{W propellant}}{\text{W total}}$ |
| $f_4$ | mass fraction of shuttle system(s), $\frac{\text{W propellant}}{\text{W total}}$ |
| g | gravitational constant (32.2 ft/sec/sec) |
| h | ratio of propellant boiloff per day to initial propellant weight of the lander propulsion system, $\frac{\text{W boiloff per day}}{\text{W total propellant}}$ |
| 1-2 | velocity increment required for midcourse (fps) |
| 2-3 | velocity increment required for lunar orbit insertion (fps) |
| 5-6 | velocity increment required for lunar orbit ejection (fps) |
| $S_1$ | velocity increment required for lander-landing (fps) |
| $S_2$ | velocity increment required for lander-launch and rendezvous (fps) |
| t | $\frac{S_1}{gI_{sp_s}}$ |
| u | $\frac{S_2}{gI_{sp_s}}$ |

$I_{sp_1}$ specific impulse of midcourse system, $\frac{\text{lb - sec}}{\text{lb}}$

$I_{sp_2}$ specific impulse of insertion system, $\frac{\text{lb - sec}}{\text{lb}}$

$I_{sp_3}$ specific impulse of ejection system, $\frac{\text{lb - sec}}{\text{lb}}$

$I_{sp_4}$ specific impulse of lander system, $\frac{\text{lb - sec}}{\text{lb}}$

$W_A$ weight of lander at separation from main craft, (lb)

$W_B$ weight of lander at lunar touchdown, (lb)

$W_C$ weight of lander at lunar launch ($W_C = W_B$ less first stage propulsion system inert weight when staged) (lb)

$W_D$ weight of lander after recontact, (lb)

$W_E$ lander payload weight, (lb)

$W_G$ weight of lander crew, (lb)

$W_H$ weight of lander at separation from craft less crew weight ($W_H = W_A - W_G$), (lb)

$WO_3$ weight of lander propellant system boiloff prior to separation, (lb)

$W_1$ earth-escape weight, (lb)

$W_8$ earth-return payload weight, (lb)

## GENERAL SOLUTIONS

In order to simplify the expressions for the system weights, the velocity increments are assumed to include lunar gravitational losses. The mass fractions employed are a measure of the ratio of usable propellant to the propulsion-system gross weight. The mass fractions thus include residual liquid and vapor propellants as well as the pressurants.

The reaction-control system inert and average propellant weights are assumed to be included in the lander payload weight. The reaction-control system propellants for the translunar phase of the mission are assumed to be a constant 200 pounds for all missions. By adding this amount to the calculated earth-escape weight, an error is introduced due to the additional midcourse propellants required. This error, however, is insignificant and can be ignored. The reaction-control system propellant for the transearth phase is assumed to be 1.25 percent of the lunar escape weight. The inert weight of the main craft reaction control system is assumed to be included in the earth-return payload.

When separate propulsion systems are used for the lunar orbit insertion and ejection, the insertion system is assumed to be staged or jettisoned prior to ejection and the translunar midcourse propulsion system is also assumed to be staged in this case. In all cases, the specific impulse for the midcourse systems is assumed to be 305 pound-seconds per pound.

The lander is assumed to be jettisoned following lunar orbital rendezvous and crew transfer.

Integration of the impulse-momentum relationship

$$(-dW) \cdot I_{sp} = \frac{W}{g} \cdot \overline{dV}$$

results in

$$\ln \frac{W_1}{W_2} = \frac{\Delta V}{gI_{sp}} \qquad (1)$$

Equation (1) is utilized in this report to calculate propellant requirements.

When cryogenic propellants are used, it is assumed that the mission will not require the lunar orbit insertion system beyond 4 days, the lander system beyond 7 days, and the lunar orbit ejection system beyond 10 days. Allowable boiloff of propellants for these systems is based on these time increments.

Lunar Lander System.-

1. Without staging on the lunar surface -

Solving for initial separation weight in terms of the lander weight results in the equation

$$\frac{W_A}{W_E} = \frac{e^{\frac{\Delta V_s}{gI_{sp_4}}}}{1 - \left(\frac{1-f_4}{f_4}\right)\left[\frac{e^{\left(\frac{\Delta V_s}{gI_{sp_4}}\right)} - 1}{1-7h}\right]} \tag{2}$$

When propellant boiloff is eliminated during the total mission, this expression is simplified to

$$\frac{W_A}{W_E} = \frac{e^{\left(\frac{\Delta V_s}{gI_{sp_4}}\right)}}{1 - \left(\frac{1-f_4}{f_4}\right)\left(e^{\left(\frac{\Delta V_s}{gI_{sp_4}}\right)} - 1\right)} \tag{3}$$

When boiloff does occur, the expression for the ratio of propellant boiloff to the initial separation weight is

$$\frac{WO_3}{W_A} = \frac{7h}{1-7h}\left[1 - e^{-\left(\frac{\Delta V_s}{gI_{sp_4}}\right)}\right] \tag{4}$$

2. With staging on the lunar surface (separate landing and launch propulsion systems with the landing system jettisoned prior to launch) -

Similarly, it can be shown that the following relationships are applicable to the lunar surface staging condition:

**Cryogenic Propulsion System -**

$$\frac{W_A}{W_E} = \frac{e^{(t+u)}}{\left[1-s\left(\frac{e^t - 1}{1 - 7h}\right)\right] \cdot \left[1-s\left(\frac{e^u - 1}{1 - 7h}\right)\right]} \tag{5}$$

**Storable Propulsion System -**

$$\frac{W_A}{W_E} = \frac{e^{(t+u)}}{\left[1-s\ (e^t - 1)\right]\left[1-s\ (e^u - 1)\right]} \tag{6}$$

$$\frac{WO_3}{W_A} = 7\ he^{-t}\left[\frac{e^t - 1}{1 - 7h} + \frac{e^u - 1}{e^u(1-7h)}\left(1-s\ \frac{e^t - 1}{1 - 7h}\right)\right] \tag{7}$$

$$\text{where} \quad t = \frac{\Delta V_{s_1}}{gI_{sp_s}}$$

$$\text{and} \quad u = \frac{\Delta V_{s_2}}{gI_{sp_s}}$$

Maincraft System.-

1. Unstaged -

The approximate expression for the earth-escape weight in terms of earth-return payload weight $(W_8)$, lander gross weight less crew $(W_h)$ and lander propellant boiloff is

$$W_1 = \frac{W_8 + \beta\ W_h + \gamma\ W_3}{\alpha} + 200 \tag{8}$$

Where the 200 pounds represent an allowance for translunar reaction control system propellant and

$$\alpha = AB - C - \frac{Dqe^{-x}}{E}$$

$$\beta = AF - G - Hq$$

$$\gamma = AJ - K - \frac{2jqD}{7E}$$

$$A = e^{-z} \quad (0.99375e^{-x} - 0.0063)$$

$$B = \frac{e^{-x}}{E}\left[\left(e^{-y}\right) - 6aD\right]$$

$$C = p\ell \quad (L - 0.99375Be^{-z})$$

$$D = \frac{m + ne^{-y}}{1\text{-}10a + 6an}$$

$$E = 1 + 2ajD$$

$$F = 1 - 6aH$$

$$G = p\ell \quad (M + 0.99375\ Fe^{-z})$$

$$H = \frac{n}{1\text{-}10a + 6an}$$

$$J = \frac{2j}{7E}\left[\left(e^{-y}\right) - 6aD\right]$$

$$K = p\ell \quad (N + 0.99375\ Je^{-z})$$

$$L = 1 - \frac{2aDe^{-x}}{E}$$

[redacted]

$$M = 2aH \left(1 - \frac{2ajD}{E}\right)$$

$$N = \frac{2}{7} \left(1 - \frac{2ajD}{E}\right)$$

$$j = 1 + e^{-x}$$

$$l = 1 - e^{-x}$$

$$m = 1 - e^{-y}$$

$$n = 1 - e^{-z}$$

$$p = \frac{\left(1-f_1\right)}{f_1}$$

$$q = \frac{\left(1-f_2\right)}{f_2}$$

$$x = \frac{\Delta V_{1-2}}{gI_{sp_1}}$$

$$y = \frac{\Delta V_{2-3}}{gI_{sp_2}}$$

$$z = \frac{\Delta V_{5-6}}{gI_{sp_3}}$$

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2. Staged -

Similarly, the equation for the earth-escape weight where lunar-orbit staging is employed is

$$W_1 = \frac{W_8 + \epsilon W_H + \zeta WO_3}{\delta} + 200 \qquad (9)$$

[redacted]

[redacted]



$$\delta = \frac{N.Pe^{-x}}{Q} - (Pp\ell)$$

$$\epsilon = P - \frac{NPR}{Q}$$

$$\zeta = \frac{NPS}{Q} - \frac{2p\ell P}{7}$$

$$N = e^{-y} \left(1 + \frac{q}{1-4a}\right) - \frac{q}{1-4a}$$

$$P = \left[1 - \frac{6bn}{V\,(1-10b)}\right] . T - \frac{U}{V}$$

$$Q = 1 + \frac{2ajm}{1-4a}$$

$$R = \frac{2bjn}{V\,(1-10b)}$$

$$S = \frac{2}{7}\ j$$

$$T = e^{-z} \left[e^{-x}\,(1+p) - p - 0.0063\right]$$

$$U = \frac{rn}{1-10b}$$

$$V = \left[1 + \frac{6b}{1-10b} - \left(\frac{6b}{1-10b}\right) e^{-z}\right]$$

$$r = \frac{1-f_3}{f_3}$$



PARAMETRIC EFFECTS

For an evaluation of the effects of mass fractions, velocity increments, boiloff and staging, as well as the lander and earth-return payload weights on the earth-escape payload requirements, each variable was investigated separately.

[redacted]

A 5 percent velocity increment reserve was used throughout this evaluation unless otherwise noted.

## Lunar Lander

Mass fraction.- The effect of the variation of the lunar lander mass fraction is shown in figure 1 in terms of the ratio of the lander gross weight to its payload weight. The specific impulses of 420 and 440 pound-seconds per pound correspond to hydrogen-oxygen and hydrogen-fluorine cryogenic propellant combinations respectively and are assumed to have a boiloff rate of 1 percent per day for a total of 7 days.

The cryogenics were not considered for lunar-surface staging. The ratio of boiloff weight to lander payload weight during the 7-day period is shown in figure 2 for the two cryogenic propellant combinations.

Specific impulse.- The effect of variation of the specific impulse of the lander system on its initial weight is shown in figure 3. For the purpose of evaluation of this parameter, boiloff was not taken into account. A fixed mass fraction of 0.86 was assumed and the lander was not staged.

Velocity increments.- The effect of varying the velocity increment requirements on the lander propulsion system is shown in figure 4 for a system utilizing a specific impulse of 305 pound-seconds per pound, a mass fraction of 0.86 and without staging.

## Spacecraft Systems

Mass fraction.- Earth-escape weights are shown as a function of the mass fraction for various specific impulses in figure 5 for the mission where lunar-orbit staging of the insertion and translunar midcourse-propulsion systems is employed. The earth-return payload, which includes the command and service modules but excludes the propulsion system, was assumed to be 11,000 pounds for this evaluation. The specific impulse parameters of 285, 305 and 315 pound-seconds per pound correspond to solid propellants and pressurized and pump-fed storable propellants, respectively. The latter two conditions assume the use of mixed oxides of nitrogen and hydrazine blend propellants. The specific impulse parameters of 420 and 440 pound-seconds per pound correspond to hydrogen-oxygen and hydrogen-fluorine cryogenic systems respectively. These two also include a 1-percent per day boiloff from both main spacecraft systems, as well as the lander. The lander for the solid and storable main craft systems was assumed not to be staged and was assumed to utilize a storable system with a specific impulse of 305 pound-seconds per pound, a mass fraction of 0.86, and a payload weight of 1,800 pounds. The lander system for the cryogenic main craft systems was assumed to utilize the same propellants as the main craft. For these two cases, the same specific impulses as the main craft system were assumed in combination with a mass fraction of 0.80. The lander payload was 1,800 pounds and its propulsion system was assumed not to be staged.

Similarly, figure 6 presents the effects of mass fraction on the earth-escape weight when lunar-orbit staging is not employed.

Lunar-orbit staging.- The earth-escape weights for the specific impulse parameters of 305 and 440 pound-seconds per pound as shown in figures 5 and 6 are compared in figure 7 to variation due to lunar-orbit staging.

Propellant boiloff.- The effect of boiloff allowances on the earth-escape weight for an unstaged main craft utilizing a specific impulse of 420 pound-seconds per pound and a mass fraction of 0.85 is shown in figure 8. The lander system for this case was assumed to utilize the same specific impulse as the main craft and a payload weight of 1,800 pounds. The lander mass fraction was assumed to be 0.80 as well as an allowance of 7 days of boiloff at 1 percent per day. The earth-return payload weight was assumed to be 11,000 pounds.

Velocity increments.- The effect of varying the velocity increment requirements on the main craft propulsion system is shown in figure 9. The nominal velocity requirements are as outlined in appendix A. The specific impulse and mass fraction were assumed to be 305 pound-seconds per pound and 0.84 respectively. The earth-return payload weight was assumed to be 11,000 pounds. For the purpose of this analysis, the lander was assumed to have a payload of 1,800 pounds and an unstaged propulsion system with a specific impulse of 305 pound-seconds per pound, mass fraction of 0.86 and a reserve of 5 percent. The resulting lander gross weight was 12,950 pounds.

Earth-return payload.- The effect of variations of earth-return payload weights were investigated utilizing an unstaged main craft propulsion system having a specific impulse of 305 with the results shown in figure 10. The lander gross weight was again 12,950 pounds.

Lander gross weight.- The effect of the variation in lander initial weights (i.e. gross weight less crew) is shown in figure 11. The same conditions are assumed as in the previous case except that the earth-return payload was fixed at 11,000 pounds.

## DISCUSSION OF RESULTS

From figure 1, a lander weighing 1,800 pounds and utilizing an unstaged propulsion system with a specific impulse of 305 and a reasonable mass fraction of 0.86 results in an initial lander weight of 12,950 pounds. If staging were considered for the lander, the average mass fraction of the combined systems must be above 0.78 in order to provide any benefit towards reducing the earth-escape weight requirements. Since the additional weight associated with the added thrust chamber, tubing and controls, as well as structural changes, would probably result in a mass fraction on the order of 0.78 to 0.80, only a slight advantage may be realized in the earth-escape weight. Reliability considerations would overshadow any such weight advantage and would favor the use of an unstaged lander.

This factor is even more apparent in the main craft propulsion system. Assuming a reasonable mass fraction of 0.86 in figure 6 for an unstaged system with a specific impulse of 305 pound-seconds per pound results in an earth-escape weight of 5,500 pounds. From figure 5 it can be seen that this weight would be exceeded for a staged propulsion system unless the net mass fraction was at least 0.805. Since this is not probable, it can be concluded that an unstaged main craft propulsion system is the most economical approach to the lunar lander mission and is compatible with the Apollo mission propulsion system.

The increased earth-escape weight over the normal Apollo lunar-orbit mission will determine the required tankage size for midcourse propellants if they are normally separated from the main tanks and are not intended to be used in the translunar phase of the direct landing mission.

## CONCLUDING REMARKS

The intent of this paper was to derive the expressions for the earth-escape weight for the lunar-lander mission and to examine the various parametric effects on this weight. The primary purpose of this approach was to investigate the compatibility of the lunar-lander mission with the Apollo program.

Since the main objective of the Apollo mission is eventual direct lunar landing, no definite conclusions on the Apollo propulsion system should be drawn from this analysis. It can be concluded, however, that the unstaged Apollo mission propulsion system is compatible to the lander mission. It can also be concluded that an unstaged lander is desirable.

# APPENDIX A

## NOMINAL VELOCITY INCREMENT REQUIREMENTS

Main craft.-

| | |
|---|---|
| (a) Translunar midcourse | 350 fps |
| (b) Transfer to 100-mile apogee 5-mile perigee lunar orbit | 3,296 fps |
| (c) Lunar orbit to escape | 3,296 fps |
| (d) Transearth midcourse | 350 fps |

Lander.-

| | |
|---|---|
| (a) From orbit to touchdown with an initial T/W = 0.40 | 6,250 fps |
| (b) Launch to orbit with lift-off T/W = 1.0 | 5,750 fps |
| (c) Rendezvous | 500 fps |

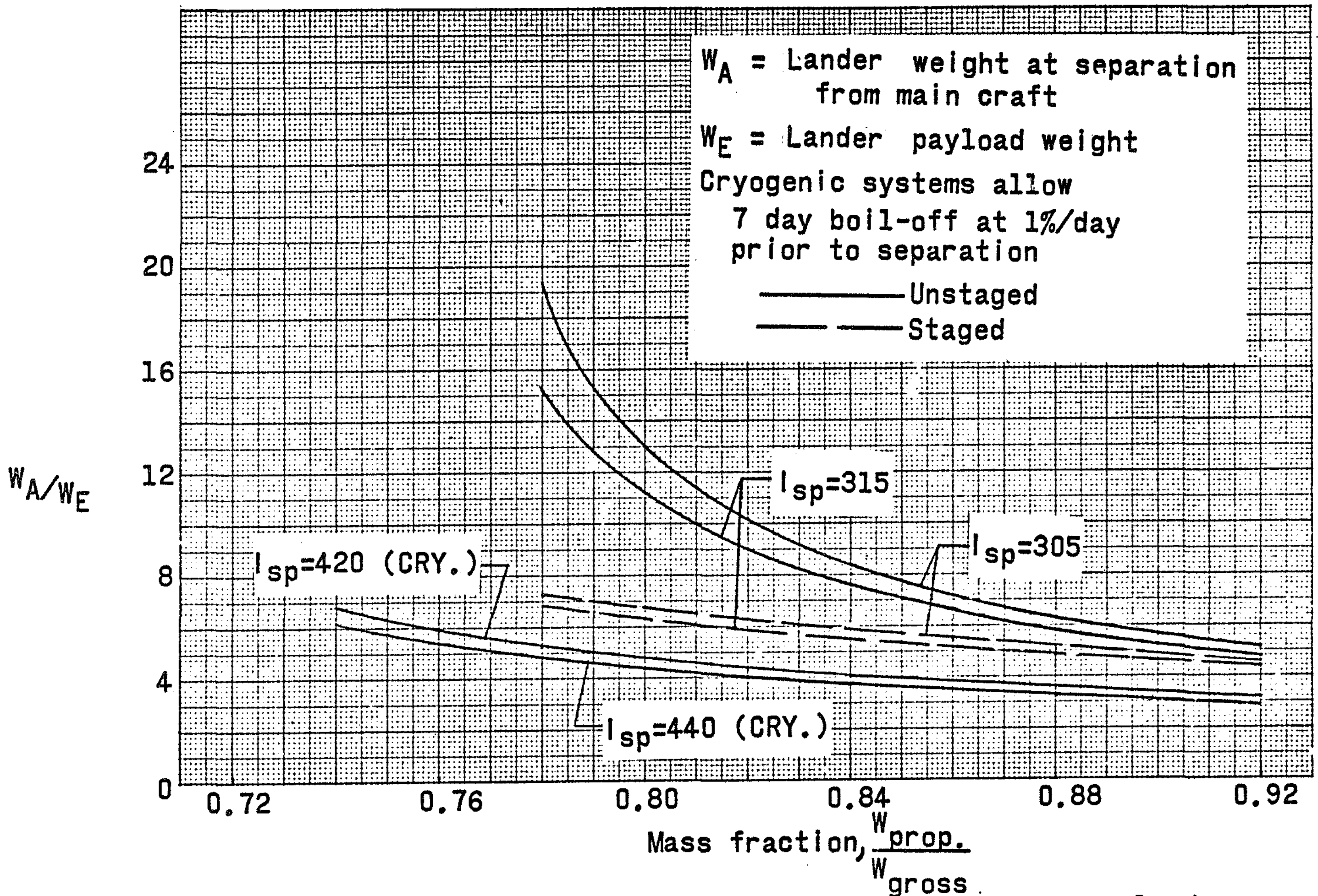


Figure 1.- Ratio of initial lander weight to lander payload.

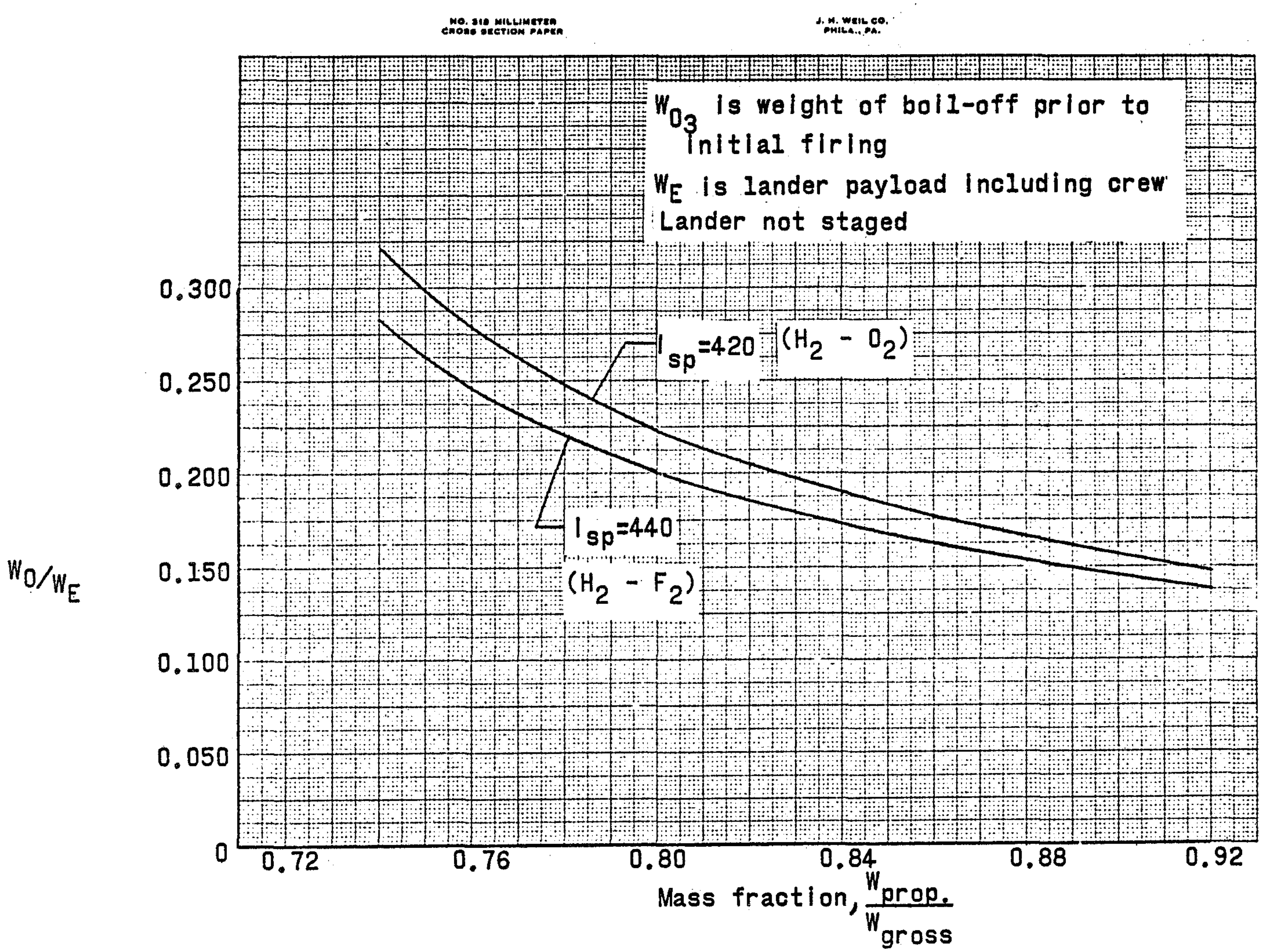


Figure 2.- Lander boil-off ratio based on maximum of seven day boil-off at one percent per day.

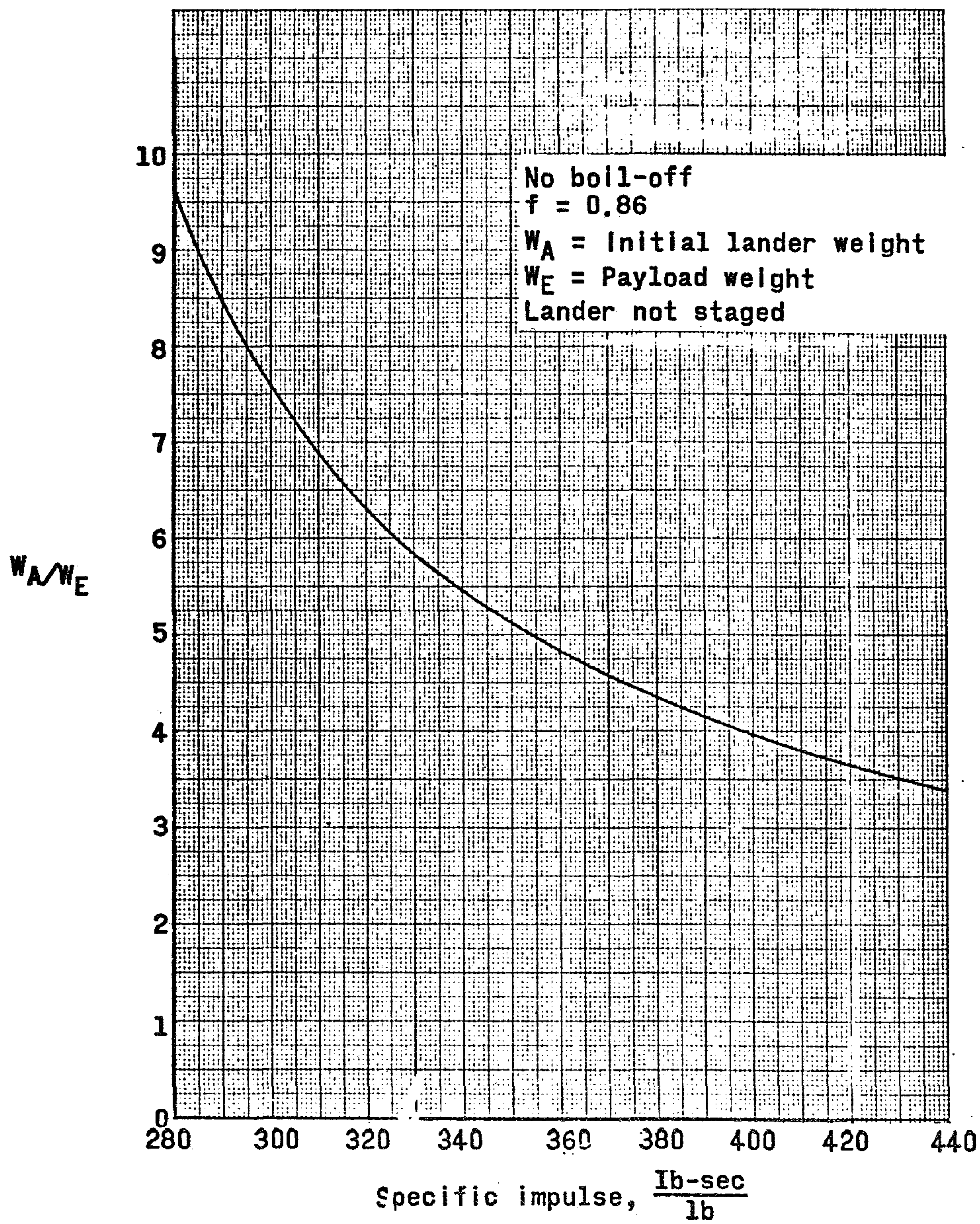


Figure 3.- Effect of specific impulse on lander weights.

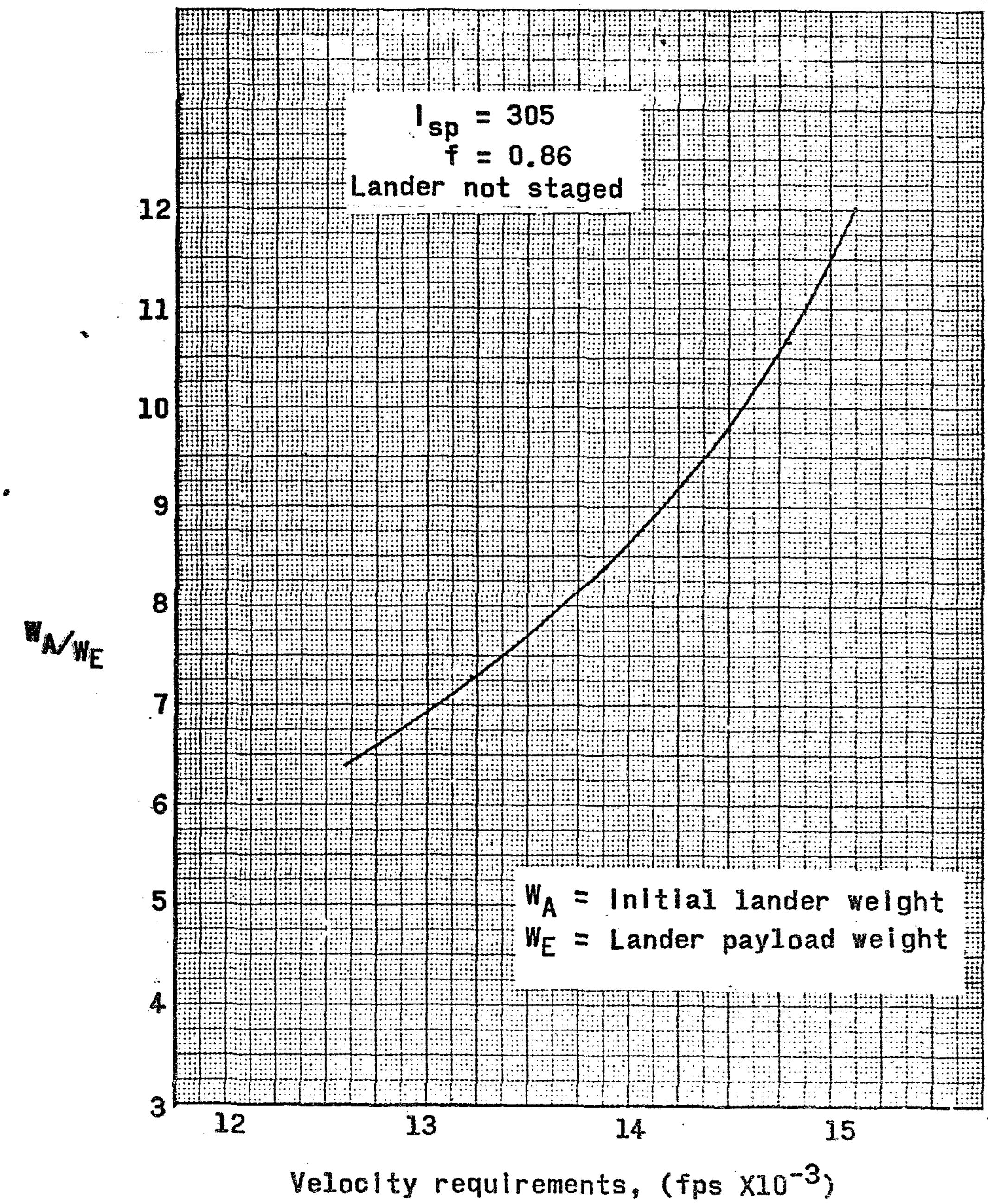


Figure 4.- Effect of total equivalent velocity requirements for lander propulsion system on lander weights.

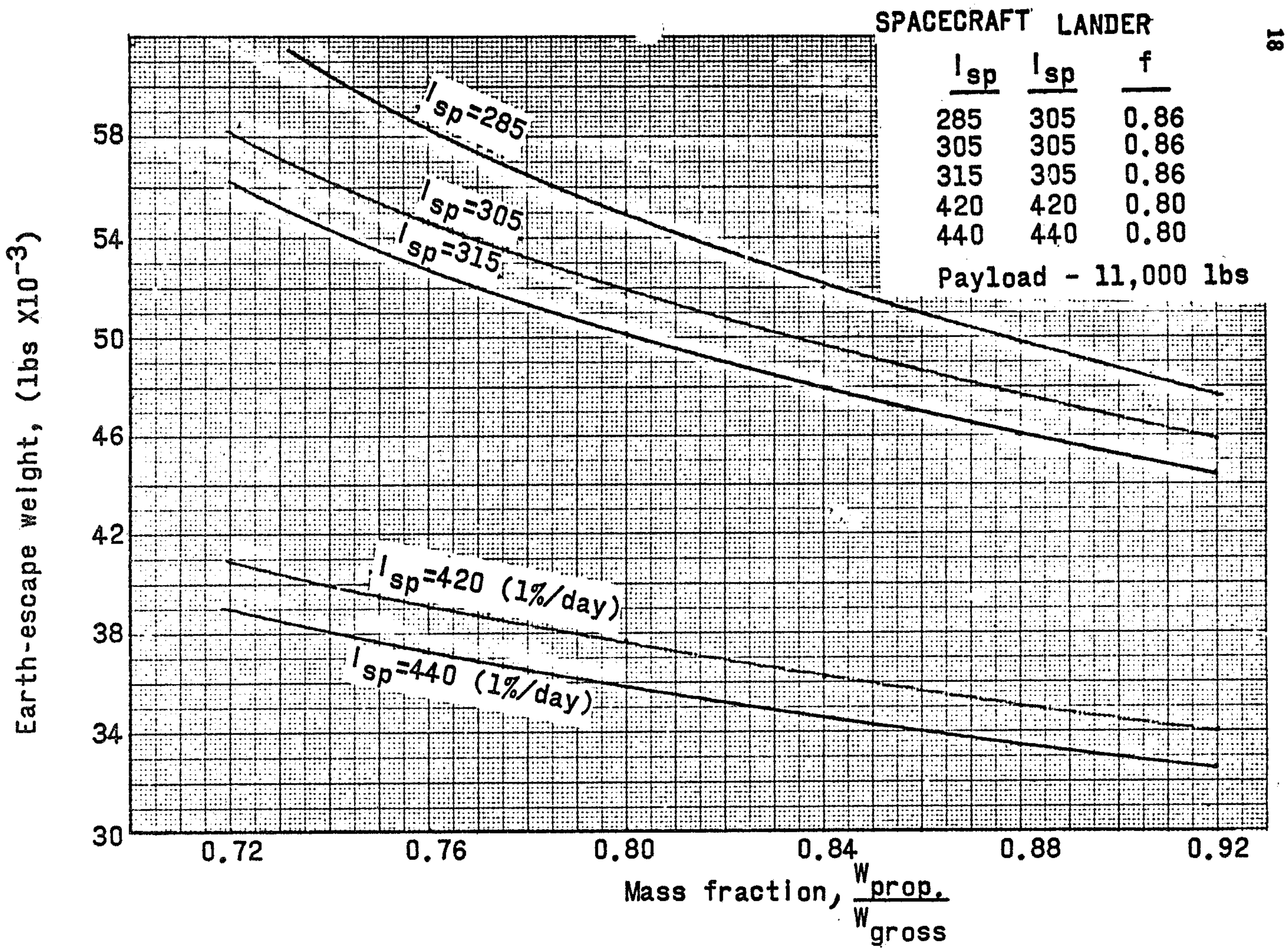


Figure 5.- Earth-escape weight with lunar-orbit staging.

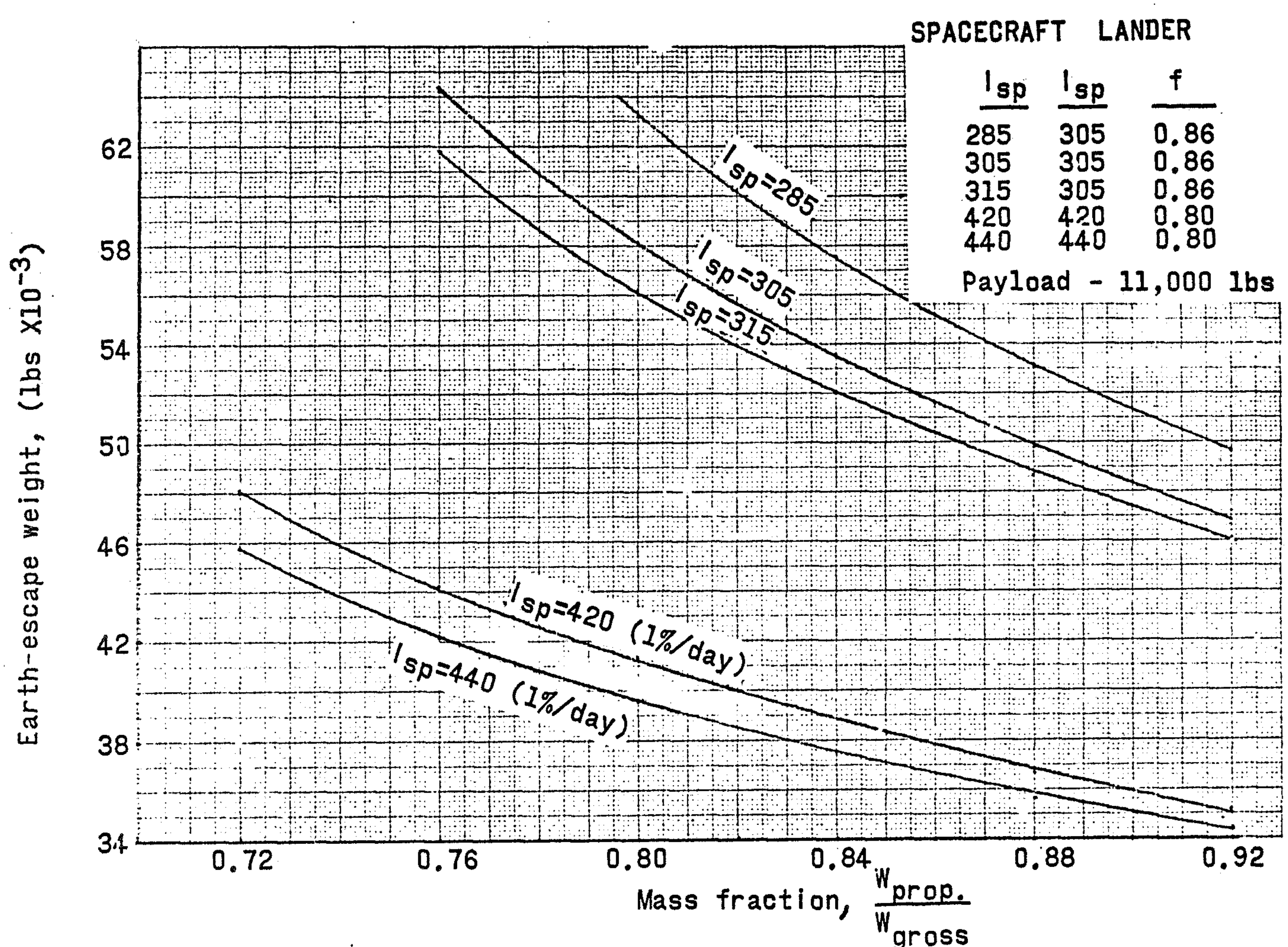


Figure 6.- Earth-escape weight without lunar-orbit staging.

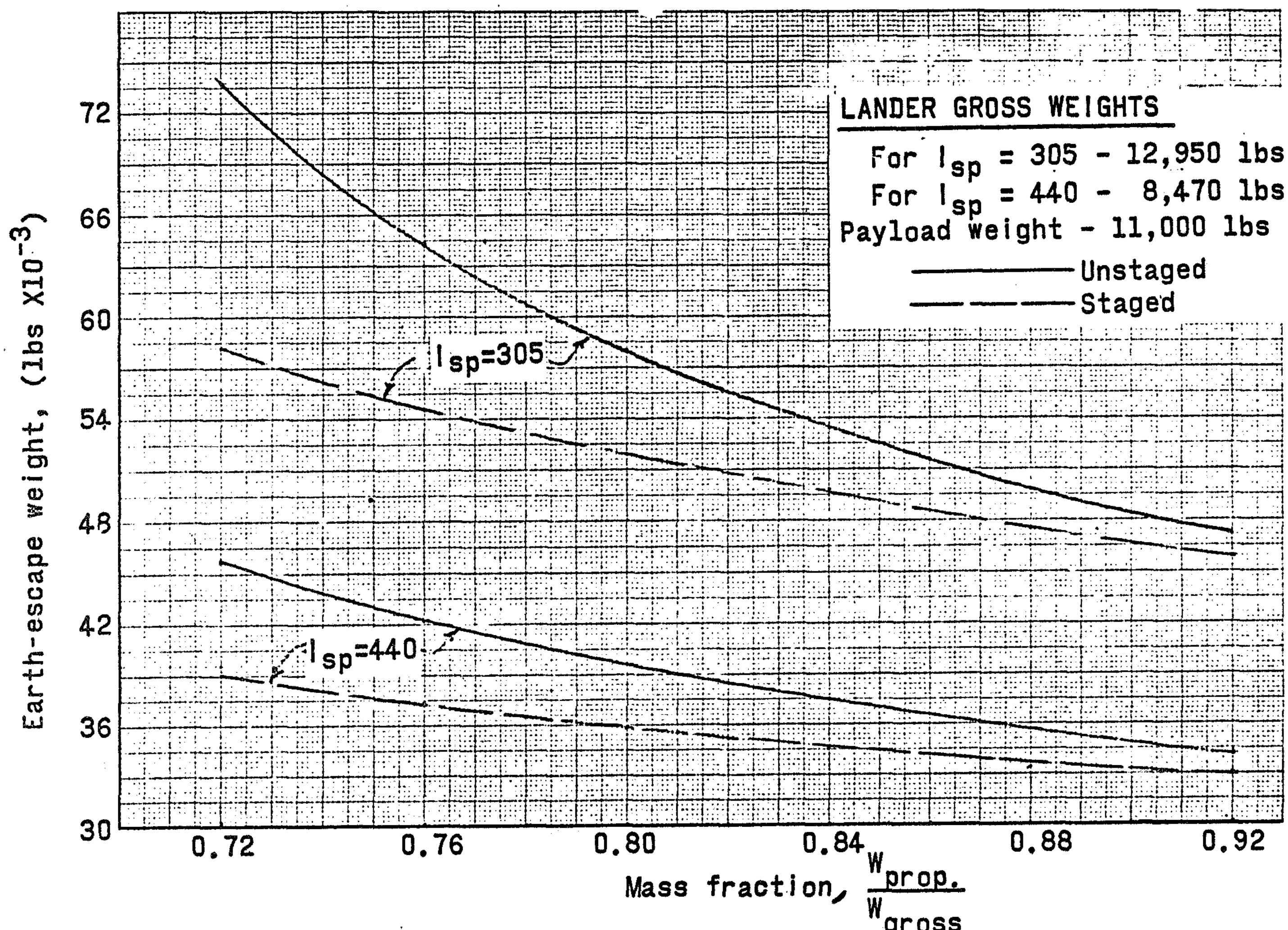


Figure 7.- Effect of lunar-orbit staging on earth-escape weight.

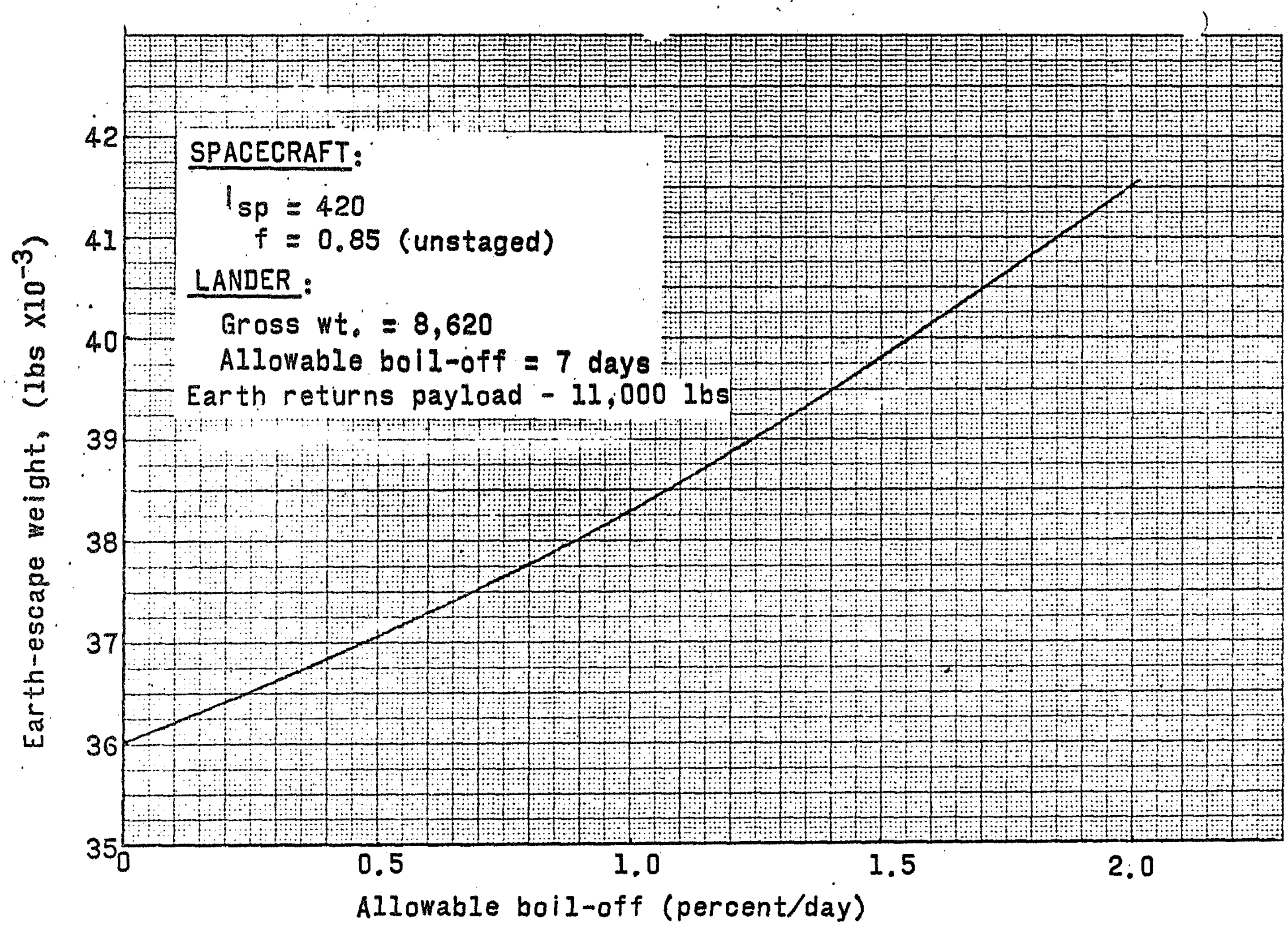


Figure 8.- Effect of boil-off of cryogenic propellants on earth-escape weight.

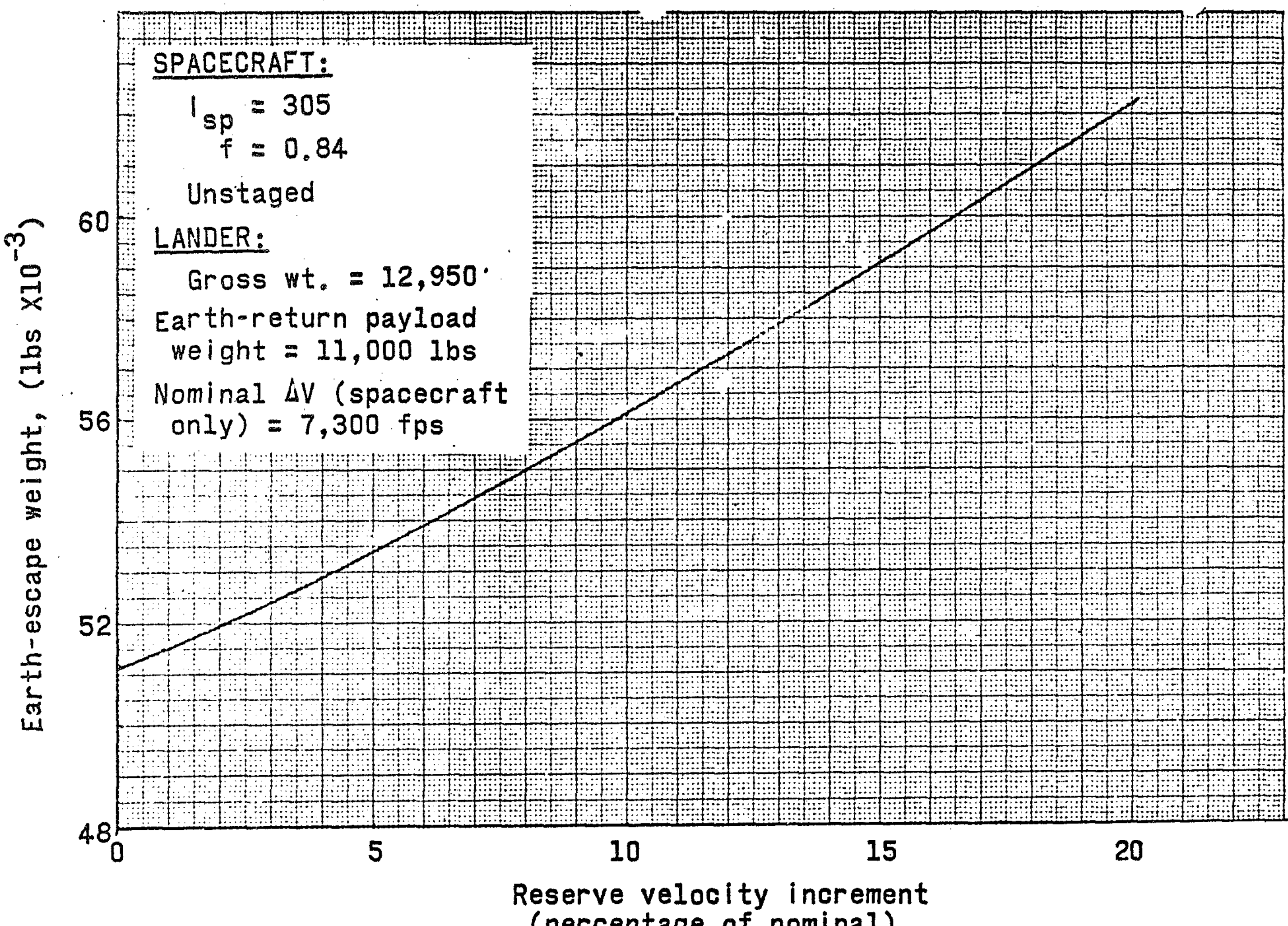


Figure 9.- Effect of reserve-velocity increment on earth-escape weight.

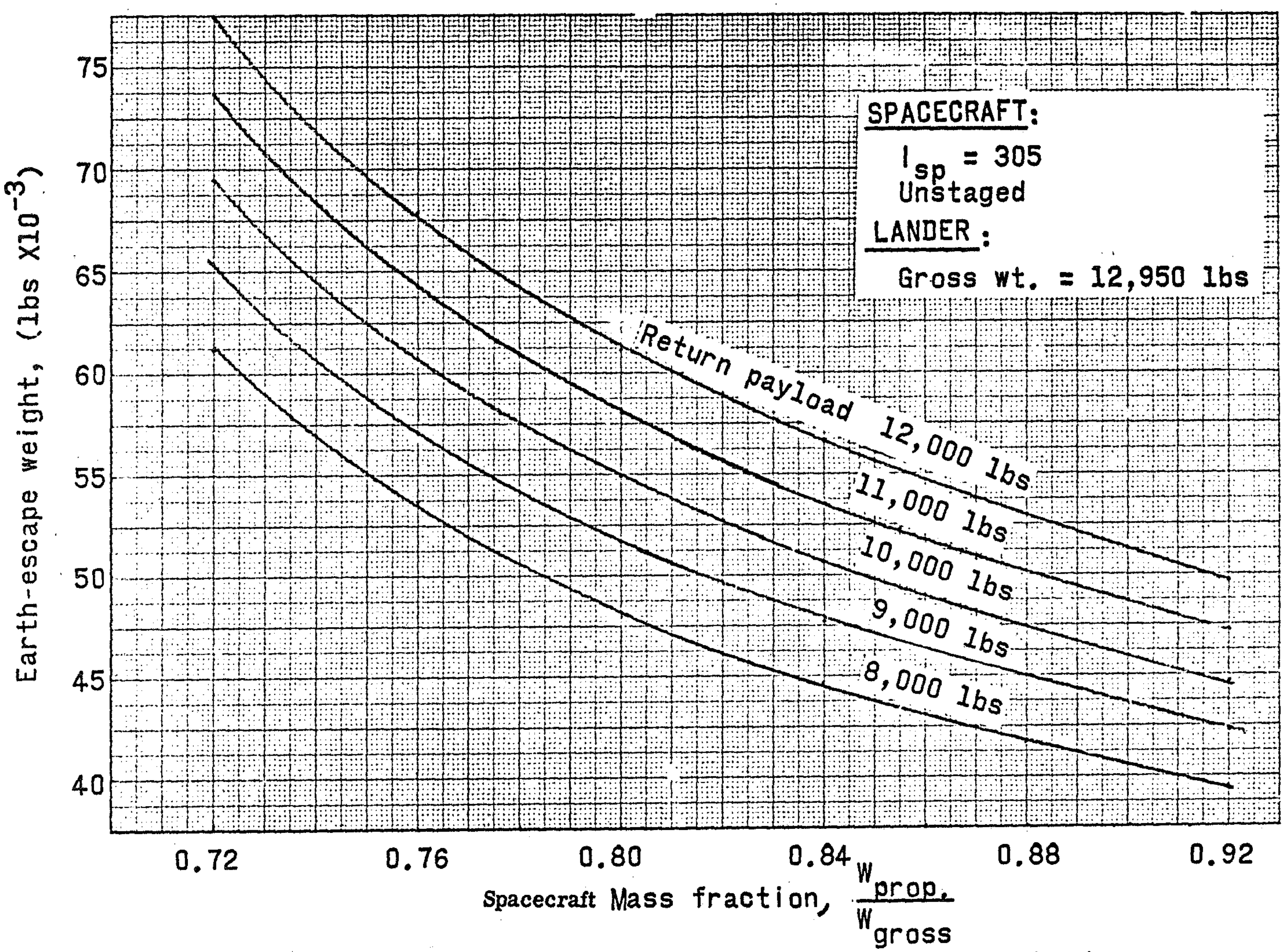


Figure 10.- Effect of variation of earth-return payload on earth-escape weight.

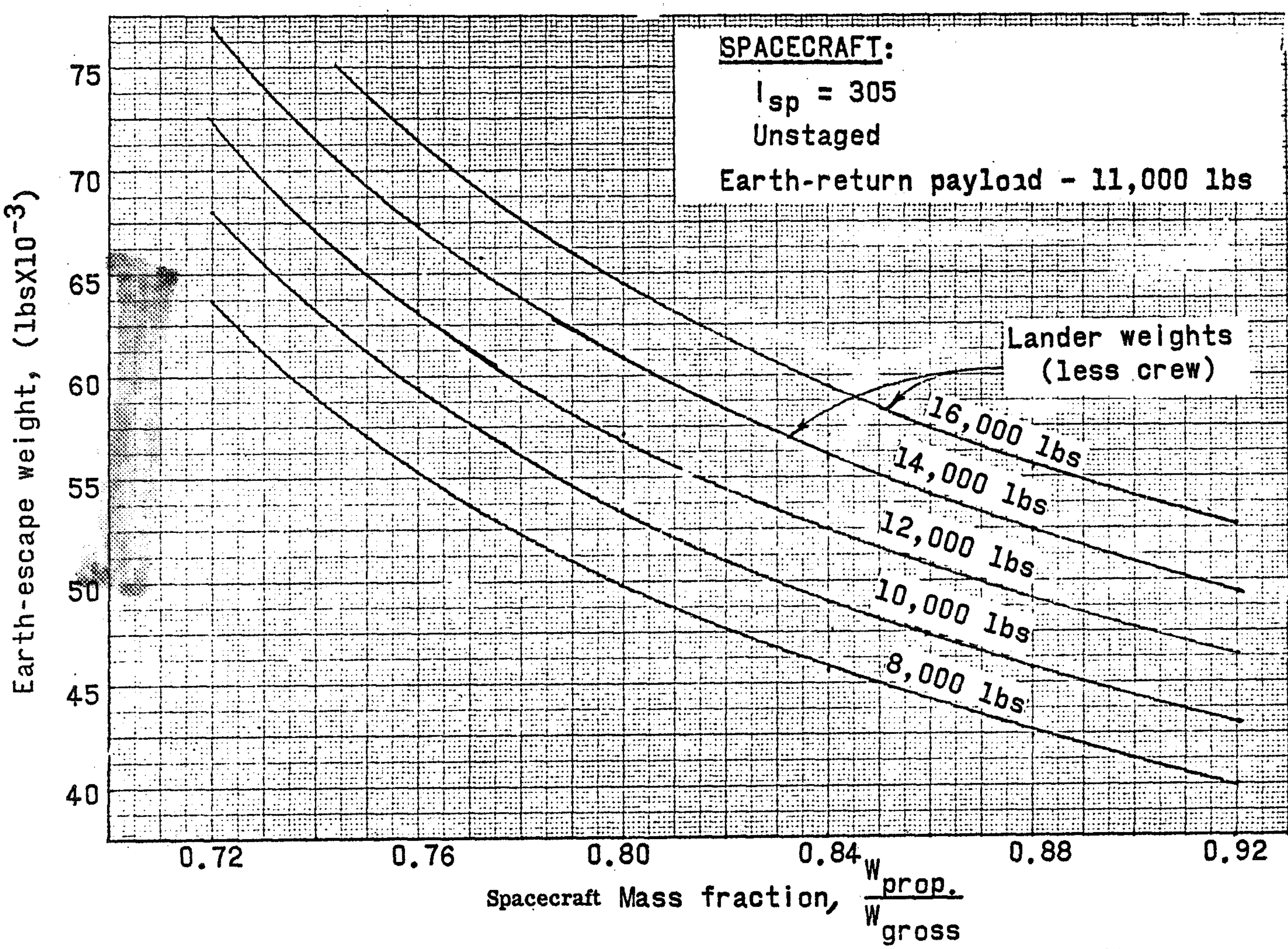


Figure 11.- Effect of variation of lander weight on earth-escape weight.

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